

# Steam explosions in boiler ash hoppers

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*Steam explosions are experienced in the ash hoppers of coal-fired boilers when hot ash falling from heat-transfer surfaces enters the water pool. Pellets of ash from three Australian power stations were formed in the laboratory and sintered under different conditions to simulate boiler ash deposits. When these were reheated and dropped into water, explosions were generated in isolated cases. The offending pellets were all lightly sintered and disintegrated into individual ash grains. The occurrence of explosions is unpredictable because of the extremely limited range of ash lump conditions under which they appear.*

## 1 INTRODUCTION

Ash hopper explosions occur in coal-fired boilers when hot ash lumps falling from heat-transfer surfaces enter the water pool of the ash hoppers under the boiler. Figure 1 shows a vertical section of a typical p.f. boiler with a water-filled ash hopper beneath. The occurrence of explosions is intermittent in nature and unpredictable. They were first discussed by Buchmueller of Deutsche Babcock in 1978 (1) and all involved boilers fired with brown coal.

A list of known explosions supplied by Babcock Australia to the author in 1985 includes boilers at a total of ten locations, in Germany, Greece, Turkey, Spain and Thailand. Brown coal boilers in Germany are now fitted with scraper conveyors in the wet ash hoppers to prevent damage from explosions. The falling ash is intercepted by a moving grate which is run just below the surface of the water in the hopper. The ash cools without being submerged and no explosions have been reported.

Buchmueller's examination of the ashes involved led to the conclusion that a minimum lump porosity of 60 per cent was required and that the material must contain a silica-alumina ratio (mass basis) of at least 10:1. This implies that the ash lumps must be mostly

sand which has not completely fused but still retains a discrete particular structure. The conclusion was supported by a photograph included in the article.

Buchmueller links the ash structure on deposition to the fusion temperature which is determined by chemical composition. Sufficient sintering between grains must take place to link the individual grains while retaining an open structure. Iron and sodium are the fluxing agents mainly responsible. The calcium content should be low. It is explicitly stated in this paper that 'steam explosions in pulverized hard coal dry bottom ash removal equipment have not been known to occur'.

This paper describes an investigation into the mechanism of explosions by means of a laboratory simulation. Ashes were collected from the hoppers of the gas cleaning equipment at three Australian stations that have experienced explosions, namely the Tarong, Bayswater and Kwinana A boilers. These were analysed and tested for explosion propensity. The ash properties tested were elemental composition, particle size distribution, true density and ash fusion temperatures.

The ashes were then formed into pellets by light pressing and sintered in a muffle furnace. They were tested for strength under axial crushing and then reheated and dropped hot into a pool of water to try to cause thermal explosions.

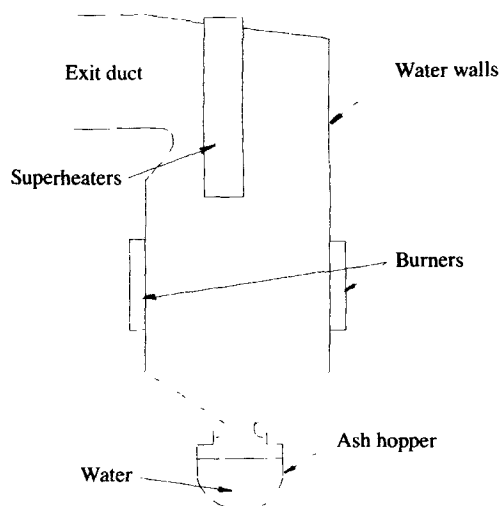


Fig. 1 Section through a typical p.f. boiler

## 1.1 Experience in Australia

The power industry in Australia has experienced a number of steam explosions in the water-filled hoppers of power station boilers. A survey of the Australian situation was carried out by the author and the results are summarized in Table 1. The coals are classified according to the ASTM system. The details listed show that events have been reported in most of the states in the country and under a range of conditions. Contrary to

Table 1 Summary of ash hopper explosions

Location	Size	Coal type	Explosions	
	MW <sub>e</sub>		Date	Frequency
Anglesea, Vic.	150	Brown	1978-83	Multiple
Eraring, NSW	660	HVB bitum	1982-3	Multiple
Tarong, Qld	350	HVC bitum	1984	Multiple
Bayswater, NSW	660	HVB bitum	1984 on	Occasional
Kwinana, WA	110	Subbitum A	1985 on	Multiple
Yallourn, Vic.	350	Brown	1989	1
Callide	350	HVC bitum	1991	1

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German experience, most of the explosions have occurred in boilers fired with hard coal.

The worst damage sustained by the boilers listed above was at Anglesea which experienced frequent explosions over a period of years. In some incidents, the insulation and cladding around the throat area were blown away and in one case the end was blown off the hopper. For some time the boiler was run with explosion mats covering the hopper walls.

The Anglesea boiler is a single corner-fired unit located near a beach. The brown coal fuel often contains sandy inclusions and this is likely to have caused the problem. The IDT of the one sample tested was very low at 1140°C and total fusion (flow) occurred below 1400°C. It contained 20 per cent iron and was rich in sulphur. After a long history of explosions in the Anglesea boiler, the ash hopper was modified to run dry.

The New South Wales experience involving two boilers of similar design and firing a similar coal, that is Eraring and Bayswater, is described by Sligar (2). The frequency of explosions was initially high but decreased with time. The source of the ash was believed to be eyebrows forming round the swirl burner ports. Some hoppers were instrumented with accelerometers but the significant pressure excursions recorded could not be linked exclusively to large clinker lumps breaking away.

The accelerometers showed that some boilers were worse than others, even though they were of identical construction and fired the same coal. Analyses of the ash showed a porosity of around 25 per cent and a mean  $\text{SiO}_2\text{--Al}_2\text{O}_3$  ratio of 3 : 1 (maximum 5.6 : 1). Ash removed from the hoppers of the Vales Point boilers, which burn a similar coal in a tangential corner firing pattern, returned a porosity of 75 per cent but no explosions have been experienced in those units.

The chemical conditions stipulated by Buchmueller for explosion occurrence are thus invalid in this case. The porosity requirement appears to be specific to the brown coal situation. However, the other physical condition specified for the ash lumps, viz. lightly sintered, still appears to be a likely criterion.

All burners at Eraring and Bayswater were modified from the original design to remove all but the minimum amount of refractory around the ports. This led to a decrease in the formation of eyebrows and to fewer explosions.

A series of explosions was experienced at Tarong in 1984 following the commissioning of the first unit, and after three weeks it was removed from service for modifications. Examination of the ash reinforced the conclusion that the conditions necessary for ash hopper explosions are not as specific as proposed by Buchmueller. The Tarong ash is very refractory with virtually no fluxing elements present (see Tables 2 and 3). The initial deformation temperature (reducing) is generally around

**Table 3** Elemental analysis of ash (% mass) by X-ray diffraction

Oxide	Tarong	Bayswater	Collie
$\text{SiO}_2$	75.8	60.6	49.1
$\text{Al}_2\text{O}_3$	21.1	25.5	32.9
$\text{Fe}_2\text{O}_3$	0.7	5.0	7.5
MgO	0.2	1.0	0.8
CaO	0.1	2.5	1.4
$\text{Na}_2\text{O}$	0.1	0.8	0.2
$\text{K}_2\text{O}$	0.40	2.97	0.54
$\text{TiO}_2$	1.28	0.99	1.58
$\text{P}_2\text{O}_5$	0.09	0.12	2.03
MnO	0.01	0.09	0.03
SrO	0.01	0.05	0.26
$\text{SO}_3$	0.02	0.09	0.54
LOI	0.07*	0.33*	3.01
Total	99.88	100.04	99.89

\* These ashes were previously ignited.

1470°C and the other fusion temperatures are above 1600°C. The silica-alumina ratio is of the order of 2–4 : 1.

The worst case currently giving concern is the Kwinana A boiler in Western Australia. This unit was originally oil-fired but was modified to burn pulverized coal. The burners are mounted on the front wall and ash is deposited at the knuckle of the bottom hopper section of the rear water wall. When the ash deposit is dislodged into the ash hopper below, explosions can result. The ash from the coal burned, which is from the Collie mine, has a  $\text{SiO}_2\text{--Al}_2\text{O}_3$  ratio of 1.5 or less, and an initial deformation temperature typically around 1450°C.

The strategies adopted to handle explosions have varied but have resulted in significant cost outlays to overcome their effects. Repairs and/or modifications have been required in almost all cases. The Tarong and Anglesea boilers are now run with dry hoppers while the burner refractory design of the two NSW boilers was modified in an effort to prevent ash buildup as eyebrows. The hoppers in all these cases were rebuilt and strengthened.

## 1.2 Literature on thermal explosions

Conventional explosives generate a shock wave when a rapid chemical reaction (combustion or detonation) generates gaseous products from a solid or liquid reactant. The increased volume of gas or vapour compresses the surrounding medium, leading to the shock wave.

In thermal explosions the gas or vapour is formed by rapid boiling of a liquid source. The only method by which such rapid heat transfer can occur is by intimate localized contact between the liquid that boils and some other medium that is at a very high temperature. Conventionally this type of explosion has involved two

**Table 2** Standard ash fusion temperatures according to AS 1038, part 15

Temperature °C	Tarong		Bayswater		Collie	
	Oxidation	Reduction	Oxidation	Reduction	Oxidation	Reduction
Initial deformation	1500	1460	1270	1250	1470	1470
Spherical	> 1600	> 1600	1430	1370	1600	1550
Hemippherical	> 1600	> 1600	1460	1400	> 1600	1550
Flow	> 1600	> 1600	1530	1500	> 1600	1590

immiscible liquids, one of which is much hotter than the other. Intimate contact between the liquids is brought about by the disruption of the heat carrier into droplets which are then dispersed into the other liquid. Typical combinations are water–molten metal, LNG–water and water–molten slag.

The engineering literature contains a wealth of information on liquid–liquid explosions, particularly in connection with nuclear science and foundry operation. A comprehensive survey was published by Reid in 1983 (3) and increasing interest in thermal explosions has resulted in further reviews, for example by Lee and Frost in 1987 (4).

During a thermal explosion the more volatile liquid is brought to a metastable superheated state by heat transfer from the other hot liquid and then undergoes an explosive phase transformation to vapour. Lee and Frost provide a detailed explanation of the liquid–liquid mechanism. They claim that the disruption of the heat carrier into fine droplets takes place in two stages. This is consistent with the delay observed in tests between the contacting of the liquids and the onset of an explosion. An experimental examination of explosions between droplets of molten tin and water by Frost and Ciccarelli (5) confirms this approach.

The first stage is a preliminary breakup into relatively large drops which are shielded from the hot surrounding liquid by a vapour film, that is by the Leidenfrost effect. This initial disruption of the hotter liquid is most likely the result of fluid drag or some other hydrodynamic effect. A diameter of 10 mm is suggested as a likely size for such drops.

The second stage begins when the vapour film around one of the larger drops undergoes collapse, generating a small vapour bubble which grows rapidly and transmits a shock wave through the surrounding liquid. The collapse of the film could be brought about by local pressure fluctuations of hydrodynamic shear. The shock wave destabilizes the vapour films around neighbouring drops and causes fragmentation. The micrometre-sized droplets formed then vaporize the surrounding liquid immediately so that the shock wave is reinforced. Thermodynamic and hydrodynamic considerations have been applied to the process and correct order-of-magnitude results have been obtained.

It has been noted by observers that salt solutions are more likely to produce explosions in liquid–liquid systems than pure water. This has been explained in terms of elevation of the homogeneous nucleation temperature, that is the lowest temperature at which a bubble of vapour can form in the pure liquid. However, Burgess (6) notes that this should have little significance in a solid–liquid system where the particles would provide nucleation sites at all temperatures.

Reid states categorically that solids will not cause such explosions (3). However, Bradfield (7) found that a cylinder of hot carbon when plunged into water produced violent phase transitions. Similarly, the experiences of the Australian power industry indicate that solids-induced thermal explosions do occur but that the conditions under which the explosions happen are very specific.

A similar mechanism to the liquid–liquid explosion could apply to solids if the millimetre-sized drops are replaced by solid ash particles. The Leidenfrost effect

can apply to larger solid lumps which then break up under a similar triggering mechanism. A crude hypothesis of this kind is the basis for a mathematical model of the system.

### 1.3 Mathematical modelling

A mathematical model of the growth of a steam bubble around a porous ash particle submerged in water was constructed by Burgess (6) following his literature survey of the phenomenon. The physical explanation put forward was that the ash lumps under water generate a steam bubble as a result of high heat-transfer rates from the ash surface to the water. A shock wave is generated in the water as the bubble grows and then collapses in milliseconds.

Burgess included the mass of ash, lump porosity, particle size, extent of water penetration and ash temperature in his list of process variables. The simulation proceeded from momentum and energy balances around the particle which calculated the rate of steam generation and hence the rate of bubble growth. Very high values for heat-transfer coefficient as reported in the literature for nucleate boiling were used in the energy balance (30 MW/m<sup>2</sup>). The results of the model verified that the postulated mechanism could produce rates of bubble growth sufficient to generate a shock wave.

The value of the Burgess model is that it demonstrates that shock waves can be generated by a hot ash–water system if the specified amount of surface contact area between the hot ash and water can be realized. For simplicity Burgess assumed that liquid water would penetrate most of the volume of the lump and be turned to steam. Such a condition is impossible in practice as film boiling would take place and the lump surface would be shielded from the liquid by a film of steam. However, if the ash lumps are lightly sintered so that they can enter the water pool intact but subsequently break up, the correct conditions can be realized.

## 2 METHOD

Flyash samples taken from the gas cleaning equipment of three Australian power stations were collected and used in a simulation aimed at reproducing ash hopper explosions. The ashes were formed into pellets, sintered at elevated temperatures and the crushing strengths of the pellets measured. They were then reheated and dropped into a trough of water to induce a thermal explosion.

### 2.1 Ash properties

The particle size distributions were measured in a Malvern 2600 laser sizer. Elemental ash analyses were determined by the X-ray diffraction. The four standard ash fusion temperatures were determined under both reducing and oxidizing conditions. The true density of each ash was determined by water displacement according to Australian Standard AS1289.

### 2.2 Pellet formation

Pellets of ash 16 mm in diameter and 25 mm in length were formed in moulds. A minimum quantity of water

was worked into the ash to give initial binding. Three different porosities were used. The pellets were then carefully removed from the moulds and allowed to dry for 24 hours in the laboratory atmosphere before being sintered in the muffle furnace. After sintering was complete the pellets were removed from the furnace, allowed to cool and stored in airtight plastic phials for testing.

Sufficient pellets were made to vary sintering conditions over a range of times and temperatures. Over 300 were made in total. The pellets were fired for 1, 3 or 5 days at sintering temperatures ranging from 800 to 1300°C. When explosions were experienced with low-temperature pellets, a closer look at temperature was instigated in the region of interest.

### 2.3 Pellet testing

The density and porosity of each of the pellet sets was calculated from the volume of the mould and the true particle density by

$$\varepsilon = 1 - \frac{m}{\rho_s V} \quad (1)$$

where

- $\varepsilon$  = pellet porosity
- $V$  = volume of mould
- $m$  = mass of ash in the pellet
- $\rho_s$  = density of ash particles

Each pellet was then crushed axially in a Geotest testing machine capable of applying forces up to 1000 N. The pellet to be crushed was retained between the working faces of the machine with 4 mm thick PVC (polyvinyl chloride) discs. The speed of approach was held to a minimum so that the onset of failure could be identified. The maximum load recorded was taken as the point of failure and the compressive strength calculated from

$$\sigma = 4 \frac{F}{\pi d^2} \left( \frac{l}{d} \right)^{0.5} \quad (2)$$

where

- $\sigma$  = compressive strength (kPa)
- $F$  = maximum load (kN)
- $d$  = pellet diameter (m)
- $l$  = pellet length (m)

The coefficient 0.5 is an empirical correction factor recommended by Petersen (8) to take account of pellet geometry.

After compression testing, the remains of the pellet were returned to the plastic phial and stored for explosion testing at a later time. Since the pellets generally failed when corners sheared off the cylinder much of the material in the pellet remained in a coherent lump. A few pellets were examined under the electron microscope.

### 2.4 Explosion testing

The largest surviving lumps of the pellets were placed on to the ceramic plates and returned to the muffle furnace, which was maintained at 800°C. As this was the lowest temperature used in the sintering step no

further sintering should have occurred over the hour in which they were held there.

When thermal soaking at 800°C was completed, each pellet was removed with tongs and immediately dropped from a height of about 100 mm above the surface into a large plastic breaker containing water. The water depth was about 150 mm and no attempt was made to control its properties or temperature. Brisbane tapwater initially at room temperature was used. As five or six pellets would be dropped at the one test, some heating of the water occurred. The outside shell of the pellet would have cooled during transfer from the furnace to the water, but this was unquantifiable.

The external microphone of a tape recorder was fixed about 100 mm above the surface of the water and at the edge of the breaker. The sounds resulting from the addition of the hot pellets to the water pool were recorded. The tape output was later sent to a cathode ray oscilloscope in order to visualize the nature of the interaction between the hot ash and the water.

## 3 RESULTS

### 3.1 Ash properties

Some of the physical properties of the ashes, i.e. densities and some particle size data are shown in Table 4. The span listed is the ratio:  $(d_{90}-d_{10})/d_{50}$ . The Tarong and Bayswater ashes are very similar in size, while Collie was generally finer. The ash fusion temperatures are given in Table 2 and the elemental analyses in Table 3.

### 3.2 Pellet manufacture

In moulding the pellets sufficient force was applied to ensure that the ash was flush with the end of the mould. The porosities calculated for the various pellets are listed in Table 5.

### 3.3 Sintering behaviour

At low temperatures the compacts were powdery in appearance and could be crushed between the fingers. The compressive strength in this condition was less than

**Table 4** Physical properties of the ashes

Ash	Density kg/m <sup>3</sup>	$d_{10}$ µm	$d_{50}$ µm	$d_{90}$ µm	Span
Tarong	2410	8	12	28	1.97
Collie	2030	4	9	17	1.35
Bayswater	2370	4	11	26	1.97

**Table 5** Calculated pellet porosities

Ash	Porosity $\varepsilon$		
	Low	Medium	High
Tarong	0.50	0.54	0.58
Collie	0.41	0.46	0.51
Bayswater	0.54	0.58	0.62

500 kPa. At higher temperatures the Collie and Bayswater pellets assumed a more glazed appearance indicating some fusion had occurred. The Bayswater and Collie pellets tended to shrink and become darker, similar in appearance to house bricks. Such pellets were very strong.

Electron micrographs of parts of a Collie pellet in a lightly sintered condition (1 day at 900°C) show isolated instances of fusion and necking between the particles. Ash bridges were also evident.

### 3.4 Strength testing

Because of the irregular structure of the pellets, there was a considerable variation in the measured strengths of pellets prepared under identical conditions. Defects often resulted in corners of the cylinders cracking off, thus causing early failure. For pellets that held together under heavy load, a common form of failure was splitting in a vertical plane (i.e. parallel to the axis of the cylinder) as a sector came away from the main body. This indicates failure in tension which was the dominant mode of failure. Progressive crumbling at the ends was also observed. With some well-sintered pellets failure occurred along a shear plane at 45° to the axis.

In the standard reference on flyash strength, Barnhardt and Williams (9) overcame the problem on non-planar ends by facing them off before testing. However, they were using samples that had been heavily compacted and would have had a more homogeneous structure. The compressive strengths they recorded are much higher than measured here, ranging from 1500 to 50 000 lb/in<sup>2</sup>. (These values correspond to 10 000 kPa and 350 000 kPa, much higher than high-strength concrete, which is given as about 70 000 kPa.)

Maximum compressive strengths of 2000 kPa were recorded for some Bayswater samples sintered at 1200°C. This value is much lower than those reported by Barnhardt but similar to those of Jung and Schobert (10). Strength was found to relate poorly to standard ash fusion temperatures, a result that has been reported elsewhere (9).

The investigation into cohesion in sintered ash compacts by Jung found that particle size had a significant effect on strength. With the finer ash particles, more contact points are formed per unit mass of compact. On sintering, 'necks' would be formed at these contact points so that high strengths would result.

No correlation was found by Wall and co-workers between initial deformation temperature and the temperature at which strength begins to appear (11). This implies that the standard ash fusion tests are only of value in ranking ash and not in predicting temperatures that will result in a suitable strength.

Leaving aside the influence of particle size, in the present study both time and temperature were important in determining compressive strength. The influence of temperature generally reflects the fusion behaviour as measured in standard ash fusion tests, with Bayswater exhibiting the lowest fusion temperatures and Tarong the highest.

The influences of time, temperature and porosity on strength were similar for all ashes and are demonstrated in Figs 2 to 5. Increasing sinter temperature leads to a growth in sinter strength, as shown in Fig. 2 for a

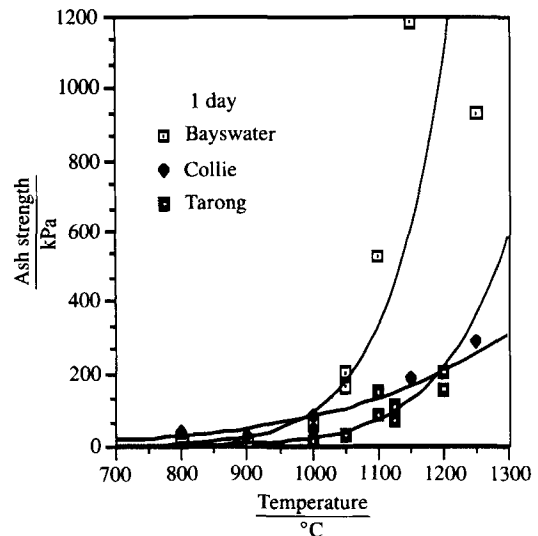


Fig. 2 Effect of temperature on crushing strength for ash pellets sintered for 1 day

period of one day and Fig. 3 for five days. As would be expected, the strengths of Bayswater and Collie, which contain the fluxing elements iron and calcium, increase rapidly with temperature. Tarong is slightly stronger at lower temperatures but is overtaken as temperature increases above 1200°C.

A corresponding increase in strength occurs with time (see Fig. 4 for Tarong ash which shows a typical response). There is a marked increase in strength between 1050° and 1100°C, indicating that sintering had become significant. Collie shows a similar increase between 900 and 1000°C.

The influence of packing density is depicted for Tarong ash pellets in Fig. 5. As anticipated, the higher voidage compacts showed a decrease in strength for the same conditions. The effect is duplicated with the other ashes.

### 3.5 Explosion testing

Over 300 pellets were made in a sequence of tests covering the sintering conditions outlined above, that is 1–5

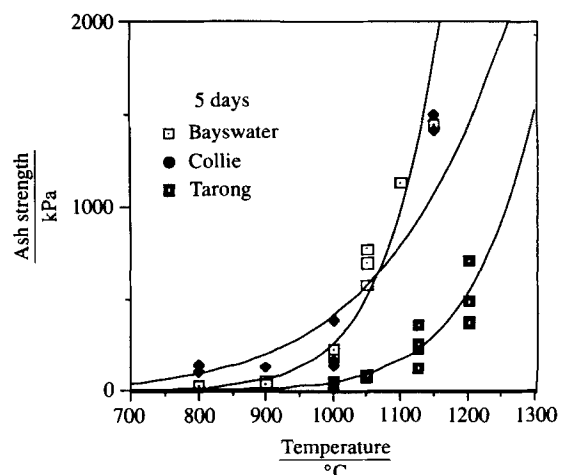


Fig. 3 Effect of temperature on crushing strength for ash pellets sintered for 5 days

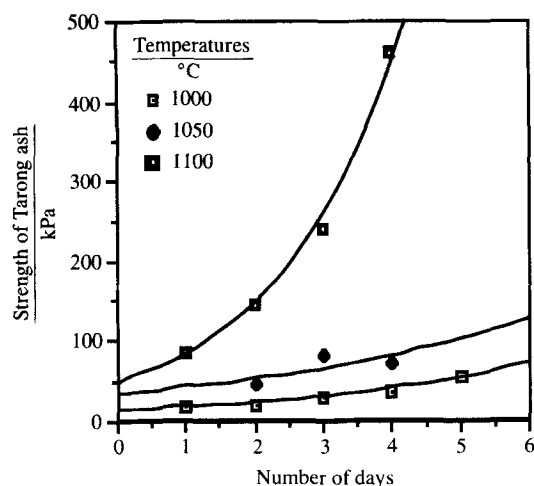


Fig. 4 Effect of sintering time on crushing strength, Tarong ash

days at a range of temperatures from 800 to 1300°C. Previously sintered pellets were placed into the oven at 800°C, held for about an hour and then removed and immediately dropped in the beaker of water. In most cases the particles sank, while fizzing and 'popping' during cooling. Some reactions were comparatively more prolonged and energetic than others, but overall very little effect was produced.

Some low-temperature pellets had only loose adhesion and were basically powder. These showed no tendency to react significantly with the water and it was only when sintering had begun and a coherent pellet was made that the reaction became vigorous.

Most lightly sintered compacts tended to break up under water and did little more than fizz. The solid residue would be a mixture of dust and small partly sintered lumps. A few, particularly from Tarong ash, floated and disintegrated rapidly while moving across the water surface. This was obviously the result of a film of steam supporting the pellet, that is the Leidenfrost effect.

Strongly sintered compacts cooled over extended periods with vigorous fizzing. They did not break up and could be recovered intact from the water.

Some typical outputs in the form of oscilloscope traces from the tape recordings are depicted in Fig. 6. The time-scale is marked on the X axis but the vertical Y scale, which should relate to the intensity of the

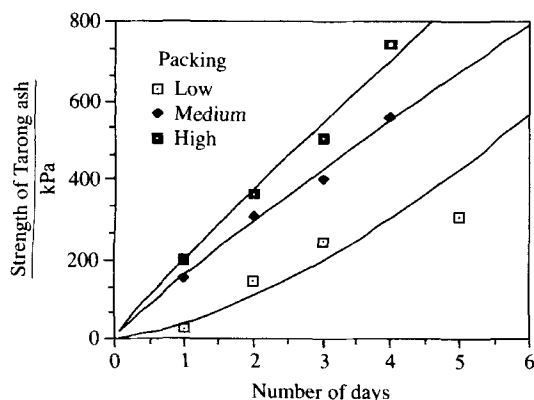


Fig. 5 Effect of voidage on crushing strength, Tarong ash

sound, has arbitrary units. Because of the tendency of the microphone system to saturate at high sound levels, the amplitudes of the traces do not accurately reflect the actual sound intensities as heard. However, they indicate the relative intensities and duration of the interaction between the pellet and the water.

Figure 6a depicts the response for a Bayswater pellet sintered for 2 days at 900°C. The reaction was comparatively short, occupying about one second. With more extensive sintering, for example 5 days at 1050°C, the duration became longer (Fig. 6b). Apparently the water takes time to penetrate into the more sintered pellets while the air trapped inside it cools and contracts, thus allowing the water to enter. Prolonged cooling of this kind was observed for all samples that had been sintered for longer times at high temperatures. The lower the sintering temperature, the shorter the duration of the cooling tended to be, presumably because the water could penetrate more easily into the open structure of the particle after immersion.

Similar behaviour was exhibited by the other ashes, although at different temperatures, which reflects their relative fusibilities. A Tarong pellet held for 2 days at 1200°C gave a response that persisted for more than 10 seconds (Fig. 6c). The longest sound recorded was for a Collie pellet sintered at 1200°C for 2 days, which continued for 14 seconds!

In general the length of interaction with water on cooling corresponds with the compressive strengths of the particles. However, there were exceptions to this kind of behaviour between different ashes. Although Collie did not give as high-strength pellets as Bayswater, it gave prolonged interactions with water during these tests.

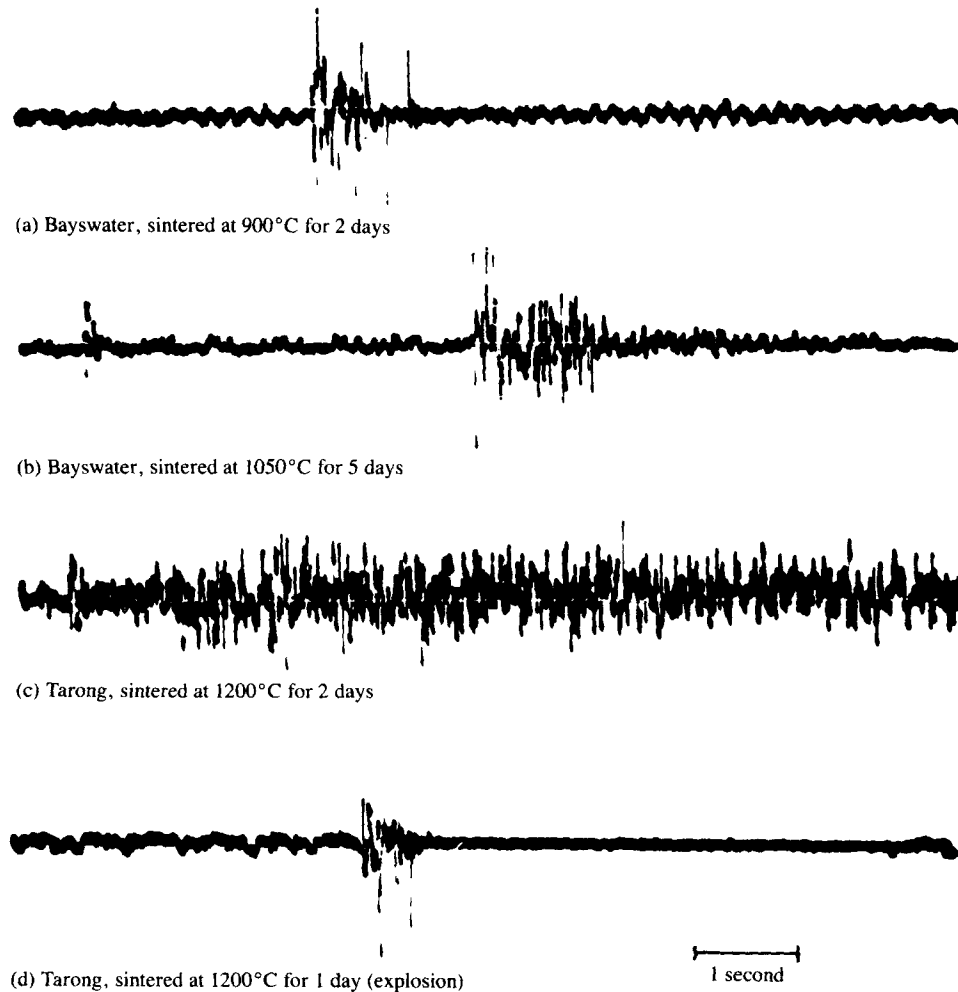
In seven cases genuine explosions resulted, mostly with Collie ash but two with Tarong and none with Bayswater. The Tarong explosions appeared during the testing sequence in two isolated cases. Duplicates under similar conditions did not behave in the same way. No explosions appeared with Collie ash during the normal sequence; those that did take place were induced under special conditions.

The most severe Collie explosion blew the beaker off the bench with a pellet of just over 5 g in weight. It is not certain whether the occurrence of explosions with Collie was because that ash is inherently more likely to cause explosions or that the correct conditions were accidentally found. Since the Tarong ash gave two results in the general testing programme and the Collie none, it was assumed that Tarong ash is more susceptible.

In every case where an explosion occurred the pellet was in a low-strength condition, that is lightly sintered. In each instance the pellet completely disintegrated, so that the ash remained either as mud on the base of the breaker or suspended in the water. With the Tarong ash, which is white, the explosions left the remaining water quite milky in appearance.

*In no case did a strongly sintered pellet or a loose powder cause an explosion.*

The observation that loose powder will not cause explosions may be true only on the small scale. There was no possibility that the loose ash forming a pellet could remain in a coherent lump on entry into the



**Fig. 6** Oscilloscope traces of microphone output during addition of ash pellets at 800°C to water

water. This would seem to be a requirement for explosions. However, in a boiler where the masses of ash involved are much larger it may be possible for an ash-slide to have its interior shielded from water for some time after immersion. In spite of this, the experience at the University of Queensland is that even kilogram-sized slugs of loose ash produce very little reaction.

A summary of the conditions for which explosions occurred is given in Table 6. The strengths shown in the table are for equivalent pellets as read from the appropriate graphs. The N/A result for some of the Collie pellets means 'not applicable' because special procedures had been adopted. These are explained in later paragraphs.

**Table 6** Summary of conditions for explosions

Test number	Ash	Temperature °C	Time days	Porosity	Likely strength kPa
98	Tarong	1000	4	0.50	60
188		1200	1	0.54	150
264	Collie	900	N/A	0.46	40
265		900	N/A	0.46	40
266		900	N/A	0.46	40
267		1000	N/A	0.46	50
268		1000	N/A	0.46	50

The explosions all display the same features on the oscilloscope trace; Fig. 6d which represents test 188 is typical. The microphone was unable to record these events accurately due to the fact that the recording system 'saturated' and temporarily switched itself off. The traces that were produced indicate that a delay period of about half a second preceded the onset of the explosion. During this delay period, a typical fizzing response was recorded. The subsequent flat portion (zero amplitude) shows where the recording system shut down due to overload. Similar traces with half-second delays were recorded for the other explosions.

It should also be noted that in tests 264 to 268, the Collie pellets were not treated normally. A batch of pellets had initially been prepared at 800°C for one day but no explosions had occurred with the furnace held at 800°C for the testing. The furnace was then rapidly raised in temperature (10°C per minute) up to 900°C, and then 1000°C and finally 1100°C. The temperature was held at each 100°C interval for as short a period as possible and drop tests carried out on two samples. The heating was then resumed.

Explosions occurred at 900 and 1000°C, but not at 1100°C. When the furnace was then quickly cooled back to 900°C, the remaining pellets no longer caused explosions. Apparently they had become too sintered and would not disintegrate, but remained as hard intact pellets on the beaker bottom.

*This procedure for Collie ash was repeated again a number of times but, although energetic interactions occurred, genuine explosions could not be produced.*

The contrast between the two types of traces, explosive and non-explosive, adds further weight to the validity of the hypothesis that rapid particle dispersion is responsible for explosions.

The way in which the pellets were sintered is apparently very important, as there were many apparently identical tests with Tarong ash of which only one exploded. Evidently a combination of correct maximum temperature and temperature history is necessary in order to produce exactly the right sintered structure in the pellet. A number of different regimes may produce the correct conditions.

The difference in sintering temperatures between the two successful Tarong tests illustrates this point. There is an increase in the strength of pellets sintered for long periods over the temperature range 1000–1200°C and yet these two apparently different pellets were the only two to explode.

Collie pellets that had been sintered for long periods (that is days) at 900 and 1000°C did not cause explosions, obviously because the extended exposure to temperature had forced the sintering process to proceed too far. At the same time most pellets sintered at 800°C did not cause explosions either. This makes it difficult to identify the precise conditions that will give explosions.

All the temperatures of sintering are well below the initial fusion temperatures of the ashes as measured in the standard Australian test (Table 2). Although these temperatures can give a guide to relative fusibility, the complexity of the fusion process precludes any correlation being based on them.

The IDT (reducing) of the Collie sample tested was 1470°C, yet explosions occurred when the ash was held in the 900–1000°C range. At 1100°C the onset of fusion caused the phenomenon to pass, even though that temperature was maintained for only a matter of minutes. The IDT of Tarong is similar to that of Collie (1460°C) but the two Tarong explosions were generated by compacts sintered at 1000 and 1200°C.

It is of interest to note that the compacts with the least porosity, namely Collie, were responsible for most explosions. This was probably a random result brought about by the nature of the testing programme. Only in that particular set of experiments did the right conditions arise. In general, an increase in porosity leads to a decrease in strength so that in boiler practice, high-porosity ash should have a greater tendency to cause explosions. No Collie pellet exceeded the 0.6 voidage criterion set by Buchmueller.

*As a result of these tests there is no doubt that lightly sintered ash is responsible for ash hopper explosions.*

The nature of the sinter necks between adjacent individual particles appears to determine the explosive potential of an ash lump. No single heating regime appears to be responsible for forming such necks. The correct condition can be met by sintering over a range of temperature/time combinations. The sinter structure will pass through the critical condition if the temperature is raised sufficiently. This condition may be met by heating near a critical temperature for an

extended period or raising the temperature rapidly but stopping the sintering process at the critical point. The important consideration for an ash explosion is that the lump enters the water while the conditions are correct.

#### 4 DISCUSSION

The question arises as to whether there are sites on heat-transfer surfaces in operating boilers where ash can be deposited and remain for long periods at temperatures low enough to cause explosions, that is 900°C for Collie and 1000–1200°C for Tarong. In an ash deposit there will be a temperature gradient ranging from saturated or superheated steam temperature at the wall to elevated temperatures on the outside surface. This outside temperature will be determined by a heat balance between conduction to the tube and radiation from the flame.

Because of the intense radiation levels in the furnace zone, the top ash layer, which was most recently deposited, will be at the highest temperature that it will experience as part of the deposit. As further ash is laid down on top of it, its temperature will fall. Any prolonged exposure will cause irreversible sintering, as found to occur at 1100°C in the laboratory tests on Collie pellets.

A heat-balance calculation can be used to estimate surface temperature and thus the temperature history of the ash deposit. Ash deposits occur in various thicknesses and conductivities but a boiler thermal survey by the author using a mathematical model has shown that a combined resistance  $\mathcal{R}$  ( $=$  thermal conductivity/thickness) should be of the order of 500 W/m<sup>2</sup> K. Over an ash deposit of thickness  $t$  and conductivity  $k$ , a heat balance then gives

radiant exchange = conduction to wall

$$\sigma \varepsilon \mathcal{F} (T_g^4 - T_s^4) = \frac{k}{t(T_s - T_w)} = \mathcal{R}(T_s - T_w) \quad (3)$$

where

- $\varepsilon$  = flame emissivity
- $\mathcal{F}$  = radiation view factor
- $T_g$  = gas temperature
- $T_s$  = ash surface temperature
- $T_w$  = tube wall temperature

At the burner zone of a modern boiler, the absorbed radiation [that is the left-hand side of equation (3)] is about 300 kW/m<sup>2</sup>. Equating this to the right-hand side gives a surface temperature  $T_s$  about 600°C above the tube temperature, that is around 950°C. This is of the right order for the Bayswater boilers where the offending ash was identified as eyebrows which formed around the burner ports.

In the Tarong case the ash probably forms on the radiant superheater tubes where the gas temperature is about 1400°C and the incident heat flux is 350 kW/m<sup>2</sup>. Given the low emissivity of the whitish Tarong ash, the absorbed radiation is likely to be 170 kW/m<sup>2</sup>. At superheater temperatures of around 550°C, this gives a surface temperature of 900°C, which is conducive to explosive ash formation.

A similar estimate for the burner region of the Kwinana A boiler firing Collie coal ( $T_g = 1450^\circ\text{C}$ ,



radiation = 220 kW/m<sup>2</sup>) gives an ash surface temperature of 800°C, which again is of the right order.

These rough calculations confirm that it is possible to form ash deposits at low temperatures. Much will depend on the condition of the ash particles as they arrive at the surface and how thick the deposit is. The nature and packing of the ash will determine the conductivity so that it is possible that  $R$ , which was an average value, can vary widely from place to place in the boiler.

A number of conditions must all be simultaneously met for suitable ash deposits to grow, and it is not surprising that in some instances explosions are experienced at very irregular intervals.

#### 4.1 Possible explosion mechanism

In each case where an explosion took place the detonation did not occur immediately upon entry of the hot lump into the water but followed a preliminary 'fizzing' (see Fig. 6d). This sound was similar to that from other non-exploding ashes. It probably results from localized evaporation-condensation effects as water penetrates into the hot particle. This corresponds to the triggering stage of the liquid-liquid explosion.

The sequence of events in solid-liquid thermal explosions in boilers could therefore parallel that for liquid-liquid explosions, that is:

- (a) entry of a major ash lump into the water pool;
- (b) fragmentation of the lump into smaller pieces either on impact or with cooling (each with a surrounding steam film);
- (c) disruption of the steam film around one fragment;
- (d) disintegration of the fragment into individual ash grains, thus forming a steam bubble;
- (e) generation of a shock wave by the growing bubble;
- (f) propagation of the shock wave to the adjacent fragments;
- (g) disruption of more vapour films by the shock wave with a cascade effect;
- (h) coalescence of the steam bubbles to form one large bubble.

The tests carried out in the laboratory are probably equivalent to the second-stage 'triggering' in the thermal explosion where the first individual fragment disintegrates. If many similar particles were in the vicinity, the first explosive disintegration would detonate the remainder.

For this sequence to take place, the lump must be able to disintegrate easily into individual grains. The strength range found for this effect to occur is in the vicinity of 200 kPa under an axial crushing test. At this value, the compact can be easily crushed between the fingers.

The question remains as to why the first fragment should disintegrate. One possible explanation is that parts of the ash mass will consist of a colder exterior shell surrounding a very hot interior. This cold shell will form as a result of radiative cooling as the lump falls through the lower part of the furnace. Order-of-magnitude calculations suggest that a thin surface shell will always be present.

If the shell allows water to penetrate at some localized region, it could be the trigger for subsequent

events. The water penetrating the lump could be vaporized by heat being conducted back from the interior. Only a small amount of water penetration would be required to produce a significant vapour pressure, which could then rupture the shell and allow access of water to the interior. Such a hypothesis is consistent with the half-second delay experienced with explosive events.

#### 4.2 Prediction of explosions from ash properties

It is clear that ash lumps will produce explosions only within a limited range of properties. In the present tests with manufactured pellets, variations in the combination of sintering time and temperature gave rise to explosive ashes. No one combination could be specified for any particular ash. Sustained sintering at a low temperature or a rapid rise to a higher temperature can apparently produce the necessary coherence in the lump.

The adhesion of the individual particles comprising the lump is the major variable and is probably best measured by some form of strength test. However, because the appropriate condition is present only in weak compacts, a great deal of scatter is found during strength measurements. Although the results are difficult to reproduce, the likely range of compressive strength is around 40–200 kPa as measured in the crushing mode.

In assessing the likelihood of ash hopper explosions (AHEs), all the surfaces on which ash can deposit must be regarded as potential formation sites. The ash properties and the localized conditions must match for a suitable deposit to form. In view of the complexity of the temperature and flow conditions and radiation fields within an operating boiler it seems unlikely that predictive techniques can be applied.

Fusion of loose ash into lumps of the correct strength to cause explosions takes place at temperatures well below the standard initial deformation temperatures. This occurs because the very light sintering required for AHEs will not be apparent in the gross behaviour of ash compacts. The very slight modification of the surface that occurred was barely visible, even when viewed by the electron microscope.

#### 4.3 Prevention of ash hopper explosions

The type of ash that causes explosions has been identified and is consistent with the experience in the German brown coal industry. However, the uncertainty associated with the conditions under which such ash will form makes it difficult to suggest strategies by which explosions could be prevented. Although a set of conditions has been specified for brown coals, these do not extrapolate to bituminous coals.

Neither the type of boiler, rank of coal, ash porosity nor ash composition offer help in the task of prediction. Chemical modification of the ash, for example by addition of a fluxing agent, may prevent the formation of weakly sintered ash at one site but may cause problems at others.

The property that offers most promise for ash treatment in a boiler is the physical strength of the deposits.

They are so weak that it should be possible to break them up without much effort. For instance, if steam sootblowers could be directed against such deposits, they should be readily dislodged. This may be consistent with reports from Tarong that explosions occurred during sootblowing. For such a strategy to work the ash deposits must be accessible to the sootblowers and would have to be removed regularly. As this would be costly in terms of steam usage and possible tube erosion, its use may not be feasible.

## 5 CONCLUSIONS

1. Contrary to the literature on the subject, thermal explosions can occur with solids.
2. Only lightly sintered ash lumps cause explosions; loose ash or highly fused lumps do not. During an explosion, the ash lump breaks up into the individual component grains.
3. It appears that any ash can cause a thermal explosion if the conditions are right. The conditions concern degree of sinter and consequently lump strength, which should be  $<200$  kPa in a crushing test.
4. Restrictive limits on chemical composition and fusion behaviour do not apply. Ash fusion temperatures are not an indicator of fusibility for this phenomenon, as all the explosion-causing ashes were formed at temperatures  $200\text{--}500^\circ\text{C}$  below the initial deformation temperatures.
5. The correct conditions are found in a narrow window which is difficult to identify or reproduce — a number of time-temperature combinations will probably succeed. The conditions are different for each ash.
6. Because of the unpredictable nature of the phenomenon, the best approach to solving an ash hopper

explosion problem lies in engineering the ash collection system to prevent them. This means using dry or sluiced hoppers or installing ash scrapers.

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